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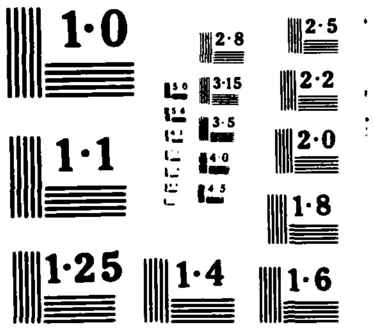
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AERONAUTICAL RESEARCH LABORATORIES

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Systems Technical Memorandum 95

A SURVEY OF AIRCRAFT INTEGRATED CONTROL TECHNOLOGY (U)

by

R.D. HILL

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SUMMARY

Current design techniques applied to aircraft flight control systems have been surveyed and the increasing use of modern control theory in the control system design of experimental technology demonstrator aircraft is described. The modern control system design methodology is seen to be particularly suitable for application to the design of controllers for complex, multivariable aircraft systems which are composed of dynamically interacting subsystems. These will typically include the flight control, propulsion and weapon systems. Some suggestions regarding the most appropriate form of future ARL involvement in this large and expanding area are made.

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CONTENTS

1. INTRODUCTION

The term "functional control integration" implies consideration of the dynamic interactions between various aircraft subsystems. Until recently, aircraft subsystems such as the airframe , inlet, engine, nozzle and weapons have been designed independently. The new integrated, or "holistic", approach considers them as one complete dynamically evolving system and the design aim then becomes one of increasing overall aircraft survivability and effectiveness. This ideally replaces the previous myriad of performance goals associated with particular subsystem components. For the next generation of aircraft, performance improvements exploiting subsystem interaction effects are likely to be considered at every stage of the design cycle. Some current and recently completed overseas research programs directed towards exploiting these potential benefits will be described.

According to Schwanz et. al. (1982) benefits from control integration will occur in the following five areas:

1) Enhanced maneuverability.

2) Precision flight path control.

3) Improved crew/vehicle interface.

4) Flight safety and availability.

5) Life cycle cost.

It is the first two of the above topics that are mainly considered in the following Sections.

2. DESIGN ASPECTS OF INTEGRATED CONTROL

2.1 Introduction

The expected improvement in survivability and mission effectiveness of future aircraft will be a result of both new hardware technologies applied to airframes, avionics,

weapons and engines and a better co-ordinated use of these new technologies. This latter, control system dependent, improvement will result from the enhancement of desirable interaction effects and the reduction or elimination of undesirable ones. The potential exploitation of such coupling between subsystems is also acting as a driver for those new technologies which provide greatest overall performance improvements. An example is the direct lift and side forces provided by a vectored nozzle capable of a variable direction thrust. The airframe and propulsion subsystems on an aircraft employing this technology will obviously be highly interactive.

The full benefit of integrated control work will be seen in the design of the next generation of aircraft, particularly military aircraft, where there is a greater scope for performance improvements. However, there is also the possibility of improving the performance of existing aircraft by reconfiguring, or adding to, existing software. Increased performance requirements and system complexity has resulted in complex control laws. It is the development of digital electronic hardware that has made feasible the practical implementation of such designs. Digital controls not only allow for the implementation of complex control laws, they also allow new control algorithms to be easily implemented.

2.2 Multivariable Control System Design

The application to aircraft of theoretical research in the area of multivariable control system design, particularly the consideration of robustness properties and design for decoupled response, is a noteworthy feature of some current work. Until very recently, despite the developments of modern control theory since the 1960's, almost all designs which have been implemented have been based on classical single-input single-output methods. The F/A-18 aircraft control laws, for example, were developed using these well proven methods - see Burton, Kneeland, Rabin and Hansen (1984). In the last few years the modern control approach has started to be used in aeronautical engineering projects. For many years the modern time domain synthesis methods were widely regarded as being too theoretical for application to practical feedback designs. Gangsaas et. al. (1986) give commonly held reasons for the failure until recently of putting the new theory into practice. These are 1) preoccupation with mathematical rigour and the notion of time domain optimality, 2) insufficient understanding of the relationship between design requirements and the mathematical formulation of the

solution, 3) failure to recognize the inherent control performance limitations imposed by the nature of the physical plant, and 4) lack of attention to the effects of uncertainty in the plant model description. In tackling these problems the paper by Doyle and Stein (1981) was noteworthy in attempting a synthesis of those classical and modern ideas which can be used by design engineers. This paper has been referred to in several publications describing large scale design projects. In particular, the problem of plant model uncertainty has been tackled in this and other papers recently. Gangsaas et. al. (1986) claim that this research has led to developments which enable multiloop synthesis and analysis to be performed with much the same ease and reliability as the classical techniques for single loop control systems. This progress is largely due to the recent attempts at bridging the gap between theory and practice.

There are several advantages claimed for *modern control* theory techniques. These all revolve around the fact that multivariable problems can be handled directly in a modern state space representation. Modern aircraft subsystems, be they for example an inlet with various input variables such as engine airflow, Mach number and angle of attack, or a highly complex turbine engine, require modelling as multi-input multi-output systems. The classical theory has solved the design and analysis problem for finite dimensional linear systems only in the single-input single-output case. For the much more difficult task of designing controllers for multivariable systems, recent literature emphasizes the need for combining classical and modern techniques. The linear quadratic gaussian (LQG) method, perhaps the cornerstone of modern control theory, has desirable robustness properties which are valuable in handling the practical problem of plant model uncertainty. One large scale project which has used a stochastic sampled-data LQG formulation is the Digital Integrated Automatic Landing System (DIALS) -see Halyo (1984). In this paper the claim is made that DIALS was the first modern control design demonstrated by flight tests on a jet class aircraft.

A major research effort with application to integrated control design is the highly maneuverable aircraft technology (HiMAT) program. A remotely piloted research vehicle has been used to investigate the integration of various advanced technologies applicable to fighter aircraft. As a part of that program an experimental flight test maneuver autopilot has been developed to provide precise control during flight test maneuvers. The control laws were derived using a combination of state space and classical design techniques (Duke et. al. (1986)). Other advanced technologies incorporated into the design were aeroelastic tailoring with composite structures and relaxed static stability.

The multivariable control system design techniques given in this Section illustrate perhaps a more "integrated" approach than in the past, because of the co-ordinated manner in which the multivariable structure is exploited. In the theoretical analysis and design of more fully integrated systems, the inherently multivariable formulation has virtually necessitated the use of a modern state space matrix representation. Indeed, in some publications there is no use made at all of the more traditional transfer function methods. See for example Fennell and Black (1982) and Murphy (1982), which examine propulsion system/airframe integration.

2.3 Model Following Techniques

A method termed model-following has been widely used in the application of modern control techniques to flight control system design. The goal with such a method is to control a system so that its outputs follow those generated by a model system which describes desired dynamic behaviour. This model has the system design specifications incorporated within it. If the control system is designed properly, the inputs to the plant, which are generated from the model inputs, the model states and the error between plant and model outputs, drive the outputs of the plant to equal the outputs of the model. There are two distinct ways in which this can be achieved. In the first, termed implicit model-following, the model is incorporated into a performance index and thus helps determine appropriate feedback gains so that deviations in the achieved transient response from the desired model response are penalized. With the second approach, explicit model-following, the model is used not only to determine appropriate feedback gains, but also feedforward gains on the model states, thus requiring an explicit simulation of the model dynamics in the controller. Broussard and Berry (1980) have applied implicit model following to the lateral control of a B-26 airplane, and also show how this technique is related to that of spectral assignment (involving eigenvalue and eigenvector placement). Okada, Kihara and Takei (1982) examine robust model following systems and apply their results to the design of the flight control system of a helicopter. Another common application involves making the short period dynamics of a linearized aircraft behave like the short period dynamics of a suitably chosen model. Other related methods of parameter optimization employ numerically more "brute force" techniques and often involve pole-placement - see Kreisselmeier and Steinhauser (1983) for application to the flight control law design of an F-4C Phantom aircraft.

2.4 Design for Robust Response

In several very recent multivariable flight control system designs employing the LQR procedure the problem of performance degradation due to incomplete sensor information has been addressed. The difficulty with the modern control approach is that many of the guaranteed desirable system properties are dependent upon the availability of perfect information from all elements of the state vector. For longitudinal flight control system design these would typically include airspeed, normal acceleration, angle of attack, pitch rate and control surface position. However, sensor information for these variables is not always accurate, and is sometimes not available at all. Angle of attack measurements, for example, are usually not very reliable and control surface deflections and their derivatives are normally not available at all. The standard procedure in such a situation is to design an observer or, if a stochastic description of errors corrupting the measurements and plant model are known, a Kalman filter to supply the missing state information. Assuming perfect state information, multivariable linear-quadratic optimal regulators have impressive robustness characteristics, including guaranteed classical gain margins of -6dB to + ∞ dB and phase margins of +60° in all channels. Unfortunately, if observers or Kalman filters are used in the implementation, there are no longer any guaranteed robustness properties. It therefore becomes important to examine robustness, because the aircraft model upon which the final design is based ignores disturbances and the variations in parameters which will occur with varying flight conditions. A controller which yields a closed loop system that is stable and retains some measure of performance despite these changes is termed robust. This is one of the major goals in flight control system design.

In tackling this problem, Doyle and Stein (1979) introduced the so-called "loop transfer recovery" (LTR) procedure, by means of which it is possible to design a system, with observers or estimators providing missing state information, whose robustness can be made arbitrarily close to that of the ideal design which assumes availability of perfect state measurements. The penalty paid for this improvement is a greater sensitivity to noise, so a trade-off will inevitably be involved.

One example of the application of the LTR procedure to aircraft controller design is given in Speyer, White, Douglas and Hull (1984). In this paper a multi-input multi-output controller design for the AFTI/F-16 aircraft is

described which decouples pitch rate and normal acceleration. As shown in Section 4.3, the fire control system makes good use of the increased maneuverability allowed by uncoupled motion control in weapon pointing. Singular principal values, which are the multivariable analogues to gain and phase margins, are used to ensure that the nominal system remains robust with respect to model and parameter uncertainties. It is worth mentioning here also the necessity of employing more than one independent control surface as a system input, even for the purely longitudinal control problem, if a decoupled response is desired. For the AFTI/F-16 design mentioned above, these are the elevators and flaps. In a paper by Sobel and Shapiro (1985), which deals with eigenstructure assignment applied to the design of multimode flight control systems, the significance of extra sensors and added independent control surfaces is described. It can be shown that if control over a larger number of eigenvalues (poles), which largely determine dynamic response, is required, then either additional independent sensors, or additional independent control surfaces must be added. Improved eigenvector assignability, however, which is required for decoupled response design, is achievable only through the provision of an increased number of independent control surfaces. If there is only a single control surface, then there is no control over the eigenvectors. This is equivalent to saying there is no control over the closed loop transfer function zeros.

Another flight control design example, this time for a short take-off and landing aircraft, is described in Gross, Houston and Maybeck (1986). The first part of this design uses implicit model following, with reduced order proportional plus integral feedback controllers. The LTR methodology is then used to preserve as much robustness as possible when a Kalman filter is embedded in the loop.

For application of these techniques to the control system design of modern transport aircraft, see Gangsaas et. al. (1986). Although the examples discussed are only modelled with a single input, and therefore do not fully exploit the power of modern time domain techniques, advantages compared with more traditional methods are demonstrated.

Robustness is also an important consideration in the design of multivariable reconfigurable flight controls. The goal with such designs is for multiple control surfaces to be used in such a way that damage to any one can be compensated for by reconfiguring, in real-time, the control of those remaining. Robust control, which is itself a form of inherent reconfigurable control, can provide the time and latitude for the identification and adaptation needed by other strategies to solve the reconfiguration problem following a control surface failure.

2.5 Porter's Method

Several multivariable digital flight control designs have been performed using a method due to Porter (1981), although apparently none of them have yet been implemented. Some of these are described in Simmers (1983), Bauschlicher (1982) and Smyth (1981). Porter's method is claimed by its proponents to be easier to use than the LQG procedure, because of the difficulty with LQG of finding a systematic way of selecting the weights to be used in the cost function. The method is also readily applied because only the steady state transfer function matrix $G = G(0) = -CA^{-1}B$ is required, which is much easier to obtain than A, B and C. Assuming a stable and non-minimum phase open loop plant, set-point tracking and good disturbance rejection are guaranteed by feeding back both the error between command input and plant output as well as the integral of this error.

Feldmann (1984) discusses the application of Porter's method to the digital flight control system design of the X-29 aircraft. The X-29 aircraft will demonstrate and evaluate advanced high risk, and high payoff technologies. In particular, it is planned to expand earlier work on aerodynamic and structural analytical design methods, digital flight control system design techniques, composite research and system integration experience. The airframe demonstrates several advanced technologies, such as forward swept wings, canards and strakes, and the control design is integrated in the sense that inputs include canards, symmetrical flaperons, strake-flaperons, thrust, rudder and differential flaperons. An integrated flight control computer is used to automatically control optimum wing shape during steady level flight.

2.6 Decentralized Control

Decentralized control is an area of modern control research which is starting to find application in aircraft control system design. As with an integrated model, the complete aircraft, including subsystem dynamic interaction effects, is analyzed, but only measurements and control devices which are local to a particular subsystem are used. Most control system design methods assume centrality, with all information available about the system, and the calculations based upon this information, handled at a

single location. In decentralized control the impracticality of simultaneously handling data from all subsystems is recognized and the assumption of centrality is discarded. Some applications to aircraft are described in Halyo and Broussard (1983) and Schwanz (1983), and the use of observers to supply missing state information in decentralized control problems is discussed in Shahian (1986). In a sense aircraft decentralized control is a compromise between the traditional method of designing subsystems completely independently, and a fully integrated design. A decentralized control design attempts full dynamic control of the aircraft using a larger measurement set than in the traditional scheme.

Unfortunately, the theory of decentralized control is not nearly as well developed as its centralized counterpart. A famous counterexample by Witsenhausen (1968) has shown that the optimal decentralized control problem for linear plants with Gaussian statistics and quadratic cost criteria does not necessarily result in a linear system. Furthermore, if the constraint is added that only linear systems be allowed, then the optimal solution may be of infinite order. Thus, even assuming that all the states are available for measurement, many desirable features of centralized LQG designs, such as simplicity and automatic satisfaction of stability and robustness properties, are lost in decentralized design.

In engineering decentralized design studies the system is broken down into interconnected subsystems, each of which is supposed stable. The design then attempts to optimize in some way the extent of interconnection between subsystems, as well as ensuring overall stability. See, for example, Grujic and Siljak (1973) and Porter and Michel (1974).

3. INTEGRATED FLIGHT CONTROL AND PROPULSION SYSTEM DESIGN

3.1 Introduction

Aircraft currently in production have had their flight and propulsion control systems designed largely independently. For missions requiring co-ordinated flight control and propulsion system commands, such as in terrain following, the pilot acts as the controls integrator. As indicated in Section 3.2, the development of autothrottles has only been partly successful in easing the pilot's workload in performing this task. The next generation of

fighter aircraft will have variable forces and moments provided by the propulsion system as an aid to path control. Propulsive devices under development include blown flaps for lift enhancement and thrust vectoring/thrust reversing exhaust nozzles for longitudinal and lateral directional control.

The Design Methods for Integrated Control Systems (DMICS) program is researching the design of integrated flight/propulsion control laws for advanced tactical aircraft. In Smith et. al. (1985) control laws have been developed for the terrain following/terrain avoidance and supersonic cruise mission segments. As for the integrated designs mentioned in Section 2.2, the large number of control effectors necessitated a multivariable approach. The design techniques have mainly employed the LQG/LTR methodology, the advantages of which have been discussed in Section 2.4.

The Highly Integrated Digital Electronic Control (HIDEC) program has demonstrated improved mission performance for an F-15 aircraft in a flightpath management mode and in an adaptive engine stall margin mode (Burcham and Haering (1984), Yonke et. al (1984)). In the stall margin mode the inlet distortion and stall margin are continuously monitored. At certain flight conditions it then becomes possible to safely demand more thrust, with a consequent improvement in mission performance. It is anticipated that these modes will be used on future advanced fighter aircraft. For an extensive review of the history of flight and engine control and control coupling techniques up to 1975, see Heimbold et. al. (1975).

3.2 Integrated Flight Path and Air Speed Control

During 1979 - 1981 NASA funded a research effort for the conceptual development of an integrated aircraft vertical flight path and air speed control system. The conventional approach is to fix thrust when the autopilot path control is engaged , and to fix elevator when the autothrottle speed control is engaged. This can lead to instability and other problems discussed in Lambregts (1983a). By coupling the airframe and propulsion system, and thereby varying the thrust and elevator in a co-ordinated manner, performance was significantly improved. In this formulation the thrust is used to control total energy, not speed, and the elevator controls the desired energy distribution between the flight path angle and acceleration. The primary control design aim becomes the provision of decoupled flight

path and speed control. Performance was simulated on a Boeing 737 and a Boeing 747, see Lambregts (1983b).

In Munger, Carlin and Gangsaas (1983) a similar decoupling of flight path and airspeed was achieved in a control law design for the AFTI (Advanced Fighter Technology Integration)/F-111 aircraft. The LQG design method was used to co-ordinate the leading and trailing edge flaps, stabilons and engines. As with the above mentioned design, the control law was not implemented on a real aircraft. Final design evaluation was performed on a nonlinear six degree-of-freedom real-time piloted simulation. A later application of the concept of measuring and controlling total energy is given in Belcastro and Ostroff (1985). In this project discrete optimal control with model following was used to control a transport aircraft landing through a severe wind shear and gust environment.

In Bangert, et. al. (1983) the impact of integrating the flight and propulsion systems on system effectiveness, including safety, mission reliability, maintainability and availability, was assessed. The study was performed on a modified YF 12 aircraft. Advanced technologies which were assumed applicable included distributed computer networks, fault tolerant computers and software, advanced direct drive actuators, fibre optic data buses and VLSI microcircuits. The integrated architecture was found to be far superior, due largely to a reduction in the number of sensors and actuators needed, and because of fewer power source requirements.

4. FLIGHT CONTROL AND WEAPON SYSTEMS INTEGRATION

4.1 Introduction

In this Section some of the operational benefits of increased maneuverability and weapon delivery accuracy are described. Until recently there were still doubts about their usefulness in an operational environment (Citurs (1984)).

Maneuverability is defined as the ability to change the direction and magnitude of an aircraft's velocity vector. During a mission the maneuvering capabilities of an aircraft in relation to airspeed determine how closely the terrain can be followed , thereby helping to avoid radar detection and infra-red surface-to-air missiles. When avoiding obstacles and closely following the terrain, the ability to

vary altitude without greatly altering aircraft attitude improves the pilot's vision and gives increased confidence at very low levels. These considerations apply both when the aircraft is under manual control and, as in Section 5, when a trajectory is computed automatically.

The wings level turn has been demonstrated to increase accuracy and survivability in the air-to-surface delivery of conventional weapons. Lateral direct side force generation permits obstacle avoidance without having to bank and turn the aircraft, a maneuver which can be dangerous at low level flight. In contrast to this, for the final stages of an air-to-ground bombing mission a maneuvering, non-wings-level delivery can be used to confound the linear predictor trackers of defensive missile sites.

The use of vertical path control is of assistance in the pull-out phase of the dive bombing maneuver, allowing operations at a lower altitude. Wings level turns and, to a lesser extent, vertical path control and the translation modes have been shown to be useful in the nulling of steering errors in air-to-air engagements. Automatic fuselage aiming (see Section 4.3) allows the pilot to concentrate on gross maneuvering, while the integrated flight/fire control system performs the fine tracking. A description of the use of such technologies on the AFTI/F-16 is given in Ramage and Bennett (1986).

The use of translation and fuselage pointing has several advantages in air-to-surface strafing. Lateral translation accounts for cross winds, while elevation fuselage aiming allows a firing solution at a lower altitude for a given slant range to the target.

In many studies, the blending of uncoupled responses with conventional control has resulted in quicker, more precise aircraft control. Improved response to gusts and turbulence has also been found. This improvement in ride qualities is important for increased pilot confidence and comfort in high speed, low level flight.

4.2 **Sensors**

The sensors provide information for the task of target identification and tracking, and thus are a vital input to the problem of generating mission effective aircraft trajectories.

Current avionic sensors cover the full frequency spectrum, from microwave radar, through infra-red, to

visible light (television and lasers). Because of its ability to gather data at night and in bad weather, the radar sensor has become a primary avionics subsystem in the modern fighter. Its disadvantages are a limited resolution in both range and angle and glint. It has good long range capability and is adaptable to detection of moving targets. This makes it very useful as a detector, tracker and identifier of both air and ground targets. Radar maps geometrically comparable to photographic maps can be constructed for navigation and targeting, and accurate ranging also allows terrain following measurements.

In suitable weather conditions, the FLIR (Forward Looking Infra-Red) permits accurate detection and angle tracking of targets, although accurate range tracking is more difficult to achieve. In good weather lasers are also very useful in providing ranging and target illumination for weapon guidance. Their narrow beam yields good angular tracking and their short pulse capability allows for high range resolution.

The performance improvements obtained by the blending of sensor information from these various sources implies that sensor integration, along with flight/fire control integration and weapon/airframe integration, will remain a major research area in the future.

4.3 **The Automated Maneuvering Attack System**

Flight path control for optimal maneuvering during weapon delivery has recently been developed as part of the Automated Maneuvering Attack System (AMAS) on the AFTI/F-16. The AFTI/F-16 is a modified F-16 that integrates an advanced digital flight control system with canard control surfaces to achieve increased agility. Technologies demonstrated in the AFTI program will be used to improve the performance of future aircraft such as the Advanced Tactical Fighter. In order to compare such developments with currently deployed systems, the extent of integration of the flight control and weapon systems on the F/A-18, which has been described as the first example of an aircraft with a multimission capability as part of the design from the beginning, will be briefly described. A detailed description of the use of the weapons and sensors is given in the F/A-18 flight manual.

In the F/A-18 air-to-ground mode the radar, FLIR (Forward Looking Infra-Red), LDT (Laser Detector Tracker) and self contained sensors within some air-to-ground weapons are used for target data collection. The weapon control system detects surface targets for attack, tracks fixed or

moving targets for weapon delivery computations and automatically delivers bombs at the computed release point. The weapon flight path is pre-programmed into the mission computers. Using further real-time information, such as wind effects on the weapon and the motion of the aircraft at the time of release, an appropriate weapon release point is calculated. Command steering is used to enable the pilot to fly the aircraft to this point, at which time automatic weapon release occurs. In an alternative delivery mode the impact point is continuously computed and displayed to the pilot on the HUD (Head-Up Display). This allows the pilot more time to designate the target. In both of these modes the pilot has to execute the required weapon delivery maneuver. Thus the weapon system and flight control system on the F/A-18 are not directly linked together. It is through the pilot that co-ordination is achieved, so the timely provision of information processed from raw sensor and avionics data is essential.

The AMAS on the AFTI/F-16, in contrast, combines target state estimation, weapon delivery solution computation and flight path computation into a closed loop system. Flight path control is performed in the flight control system by nulling the steering commands from the fire control computer. These features are exploited to produce a fully integrated, tactical weapon delivery system that can handle all phases of the terminal attack mission. For bombing, this includes automated ingress steering, real-time target acquisition and tracking, weapon delivery and egress. Flight path control from engagement on ingress, through weapon release, and into egress, can be fully automatic. For aerial gunnery, target acquisition and tracking, terminal steering and breakaway are all automated. For a description of recent flight test results, see Dowden and Ford (1986).

An important feature of the AFTI/F-16 flight control system is the task-tailored multimode flight control laws, including the 6 degrees of freedom decoupled modes. Examples of some longitudinal modes are:

1) Vertical path control - normal load factor (vertical acceleration) control at constant angle of attack.

2) Vertical translation - vertical acceleration/velocity control at constant attitude.

3) Fuselage elevation aiming - fuselage angle of attack control at constant load factor.

4) Maneuver enhancement - *blending of conventional, and* either vertical path control or vertical translation, to provide quicker response and/or improved ride quality.

Better maneuvering and increased precision in flight path (for bombing) and pointing (for gunnery) control have been demonstrated through the use of task-tailored modes. A detailed description of their use is given in Toles et. al. (1984).

The AFTI/F-16 makes use of the IFFC (Integrated Flight and Fire Control) program. IFFC was a United States Air Force Program in the early 1980's with the aim of designing and testing an automatic coupler and modified flight control system which steers out tracking errors calculated by a director fire control system. The automation of fire control steering allows significant weapon delivery performance improvements. An important component of the IFFC system was the FIREFLY program, which focused on fire control system development. FIREFLY accepts data concerning aircraft and target motion and outputs steering commands which are processed by the IFFC system for input to the flight control system. The original program integrated a core director fire control with both the F-15 and F-16 aircraft. Later efforts also included the A-10. Several aircraft parameters, including airspeed vector, inertial velocity vector, inertial acceleration vector, and an estimate of the wind, are required by FIREFLY. These parameters have to be obtained from a state estimator, because they are not measured on all aircraft. An F-15B aircraft was used as a research vehicle for the combined IFFC/FIREFLY test and evaluation.

These programs and others which make use of IFFC to improve air-to-air and air-to-surface combat effectiveness have been collectively termed Integrated Flight and Weapon Control (IFWC). The ability to maneuver at high speeds and at a low altitude is exploited in many IFWC modes. Some relevant publications are Hofmann and Haake (1980), which describes automatic pop-up trajectory control and self-designation steering for laser guided bomb delivery, Murphy (1980), concerning mainly delivery of guided weapons and dispenser munitions, and Landy (1980), which gives hardware *details of the implementation on an* F-15B. Some of the flight test performance goals are given in Meyer, Crispino and Lyons (1980) thus:

AA Gunnery

3:1 Increase in expected hits.
2:1 Reduction in time to first firing opportunity.
4:1 Increase in number and duration of firing opportunities.

Demonstration of a greatly increased employment envelope in high angle, off/high line-of-sight rate encounters.

AG Gunnery and Bombing

10:1 Increase in survivability against linear predictor anti-aircraft artillery.
2:1 Increase in weapon delivery accuracy of the IFFC system over a similar non-wings-level manual maneuver for a baseline vehicle.

Retention of present wings-level weapon delivery accuracy while performing preplanned non-wings level maneuvers.

The incorporation of the IFFC results into the AFTI's F-16 technology demonstrator aircraft shows how valuable that work was.

5. OPTIMAL TRAJECTORY GENERATION

The research areas discussed so far are very relevant to current developments in combat aircraft performance. It is therefore important to maintain an awareness of such work. In addition, work in the area of trajectory generation has important implications for combat aircraft survivability and mission effectiveness.

Trajectory generation has been described as the key and central design philosophy for developing future integrated, automatic flight management systems (Perfitt et. al. (1982)). The desired aircraft trajectory, the definition of which will in general include velocity and attitude as well as position, can be interpreted as the "strategic" controller of the aircraft and aircraft avionics systems. Since the objective function for the trajectory generator incorporates what is desired by the pilot, all other functions of an integrated system should be designed to

satisfy the requirements imposed by the trajectory generator.

Underlying the development of such systems is the revolution in computer technology. Projected increases in on-board computing capability will allow the collection and processing of vast amounts of information from many sources. The trajectory generator will ideally continuously assess information available from aircraft sensors, from stored data such as terrain data, and from monitoring the status of the various aircraft subsystems. It will then consider the impact of present control actions on immediate and future mission segments. The control strategy which maximizes some performance measure can be selected and optimal trajectories generated.

A suitable performance measure could vary greatly for differing missions, and even from one mission segment to the next. For transport aircraft it could be simply minimum fuel consumption. For military aircraft a trade-off between mission survivability and mission effectiveness will normally be involved.

The task of optimizing a mission, that is enhancing effectiveness and increasing survivability, can be divided into three phases (see, for example, Denton, et. al. (1985)):

1) Global trajectory generation. This is performed off-line and can take into account terrain data, known threat locations and fuel optimization, and is relatively coarse - the trajectory needs to be defined to an accuracy of only a kilometre or so.

2) Real-time "fine tuning" of the above trajectory. Terrain following/terrain avoidance (TF/TA) techniques, and possibly also new threat information, can be used to refine the global trajectory.

3) Trajectory tracking. The trajectory follower determines appropriate guidance commands for the aircraft flight control system to capture and track the desired trajectory. There is always a trade-off involved in this between tracking accuracy and ride qualities. For TF/TA a decoupling of the flight path angle (vertical) and yaw (lateral) command inputs is usually performed. Asseo (1973) derives the necessary and sufficient condition for decoupling a nonlinear system with state feedback, the results of which were applied to the terrain following system of the F-111 aircraft. In future aircraft the inner loop flight control system will be a decoupled system capable of accepting directly a variety of state commands required by the fire control system, trajectory generator , TF/TA algorithms, and the pilot.

Another advantage of involvement in this area is that the TACTERM project, which is currently well underway at ARL, could be highly relevant to the real-time aspect of the computation of optimal trajectories. TACTERM is a terrain matching algorithm, based on a Kalman filter, which provides enhanced navigational accuracy for low flying aircraft. Passive terrain following and terrain avoidance, made possible by TACTERM, would then be especially useful in the air-to-ground attack mode.

The rigorous theories of optimal control or the calculus of variations can sometimes be applied to the task of minimizing an integral cost function over the total mission. The type of problem that is relevant is described in Erzberger and Lee (1979). Here a cost function consisting of the sum of fuel costs and time costs was minimized using the Pontryagin maximum principle. The results in this paper have been utilized also for fuel management during the ingress and egress phases of military missions.

When the objective function cannot be expressed in a mathematically simple form, an analytical solution, such as that sought in Erzberger and Lee (1979), is difficult or impossible to find. An example is the generation of a terrain following/terrain avoidance trajectory an aircraft can follow in order to maximize survivability by staying close to the ground and lessening the probability of radar detection. Conventional terrain following systems use only pitch axis algorithms which permit minimal lateral maneuvering by the pilot. A terrain following trajectory is essentially two dimensional and follows a predetermined ground track. With the addition of a terrain avoidance capability, lateral maneuvering can be used to seek out lower altitude trajectories which avoid higher ground. In Denton, Jones and Froeberg (1985), dynamic programming techniques have been applied to this problem. Stored terrain data and aircraft properties are used to obtain optimal flyable trajectories. Other algorithms derived for application to this problem have used perturbation methods to find neighbouring optimal trajectories. An example is the gradient search technique applied to a modified F-15 aircraft described in Wendl and Katt (1982). All of these programs are apparently at the stage of ground based , real-time simulations and have not yet been flight tested. Lemm and Feeser (1985) have compared the performance of three optimization algorithms which provide local trajectory generation about a predefined reference path. Improvements in mission survivability compared with pure terrain following systems, and the trade-off between survivability and ride qualities were examined.

Another useful application of aircraft trajectory generation over realistic terrain is in pre-mission planning. Real-time calculations are not required for this,

so computationally expensive algorithms can be employed. A typical example is described in Mason (1983), where a technique is given for constructing air-to-ground mission profiles over actual terrain. The aim is to assess the comparative survivability of an aircraft delivering various weapons by an analysis of the exposure history of the mission profile. The technique relies on computer graphics to assist the user in creating realistic attack profiles.

6. CONCLUSIONS

The emerging aircraft design philosophy of combining flight control, propulsion control, navigation and weapon control has been described. Applications in this large and expanding area show significant pay-offs in the form of improved survivability and mission effectiveness for the next generation of combat aircraft.

Many of the projected benefits involve hardware developments and have implications which are inherent to the basic design of combat aircraft. An appropriate form of involvement in integrated control technology at ARL is recommended to be in the area of optimal trajectory generation, where much can be achieved by reconfiguring existing software. There is also the potential to take advantage of work undertaken on the terrain reference navigation system TACTERM project. The aim would be to more efficiently exploit existing hardware by intelligent real-time processing of information, including terrain and aircraft subsystem performance data.

The long term flexibility built into the F/A-18 aircraft makes possible future implementation of the Integrated Flight and Fire Control modes. All essential systems and their parameters are available on the multiplex bus, and the mission computers have been provided with spare memory capacity. Utilization of this extra avionics capability could result in significant performance improvements.

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16. ABSTRACT

Current design techniques applied to aircraft flight control systems have been surveyed and the increasing use of modern control theory in the control system design of experimental technology demonstrator aircraft is described. The modern control system design methodology is seen to be particularly suitable for application to the design of controllers for complex multivariable aircraft systems which are composed of dynamically interacting subsystems. These will typically include the flight control, propulsion and weapon systems. Some suggestions regarding the most appropriate form of future ARL involvement in this large and expanding area are made.

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